All Optical Flip-Flop Based on Coupled Laser Diodes

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Abstract

An all optical set-reset flip flop is presented that is based on two coupled identical laser diodes. The lasers are coupled so that when one of the lasers lases it quenches lasing in the other laser. The state of the flip flop is determined by which laser is currently lasing. Rate equations are used to model the flip flop and obtain steady state characteristics. The flip flop is experimentally demonstrated by use of antireflection coated laser diodes and free space optics.

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I. Introduction

Optical flip flops based on laser diodes (LD) have been extensively investigated as they have many potential applications in optical computing and telecommunications. The most important types of optical bistable laser diode devices can be classified into three broad types: 1) Absorptive bistability, 2) Two mode or polarization bistability by non-linear gain saturation, 3) Dispersive bistability. A review and explanation of these three types of bistable LDs can be found in [1].

The optical bistable system considered here is not based upon any of the above mentioned effects and doesn't rely on second order laser effects. Rather it is based on the fact that lasing at the natural lasing wavelength in a laser can be quenched when sufficient external light is injected into the laser cavity. The external light is not coherent with the lasing light. The external light is amplified by the laser gain medium. Lasing is quenched because the amplified external light causes the gain inside the laser to drop below the lasing threshold (for the laser's natural lasing wavelength).

The concept of a bistable laser system based on gain quenching was first envisioned in [2]. However two decades passed before the concept was experimentally demonstrated in pulsed operation with dye lasers [3]. A theoretical study of the system was presented in [4] and suggestions for implementation in laser diodes given. A bistable device loosely based on the ideas presented in [2] was demonstrated in [5]. However this device was not based on coupled separate lasing cavities and required saturable absorbers to change the lasing thresholds for the two lasing modes in the system.

In this paper we present for the first time (to our knowledge) experimental results from a bistable system based on the concept given in [2] operating continuously and employing laser diodes. Furthermore we demonstrate all optical set-reset switching of the system.

To introduce the rest of the paper, the concept presented in [2] and [4] is now elaborated in the context of the experimental system described later. Two lasers can be coupled together as shown in Figure 1. Laser A's lasing

wavelength is λ_1 and only λ_1 light from laser A is injected into laser B. Laser B's lasing wavelength is λ_2 and only λ_2 light from laser B is injected into laser A. One laser acting as master can suppress lasing action in the other slave laser. With a symmetric configuration of the two lasers the role of master and slave can be interchanged. Thus the system can be in one of two states, depending on which laser is lasing. The flip flop state can be determined by noting the wavelength of the light output. The flip flop is in state 1 if light at wavelength λ_1 is output, and state 2 if wavelength λ_2 is output.

To switch between states light from outside the flip flop can be injected into the laser that is currently master. The master laser stops lasing at its natural wavelength due to the injected light. The absence of light from the master laser allows the slave laser to start lasing and become master. When the external light is removed the flip flop remains in the new state.

The flip flop described above is modeled and implemented here by using semiconductor optical amplifiers (SOA) with wavelength dependent mirrors to form the LDs. This approach was taken because light injected into the LD which is not at the lasing wavelength only passes once through the LD. Strict requirements such as the wavelength of light injected into the LDs being at one of the LD resonant frequencies are thus avoided. However, implementations based on LDs constructed in other ways are possible.

II. Rate Equations

The flip flop can be mathematically modeled using two coupled sets of rate equations (1) to (4). Each set describes one of the LDs. In particular, the number (P_A,P_B) of photons in the laser cavity at the lasing wavelength are described by one equation [(1) for LD A, (3) for LD B]. While the carrier number (N_A,N_B) in the laser cavity is described by another equation [(2) for LD A, (4) for LD B].

The effect of injected photons into the laser cavity is modeled by adding a carrier depletion term to the carrier number rate equation [6], the S_{2av} terms in (2) and (4). The S_{2av} terms are taken from the SOA model presented

in [7]. In modeling the effect of injected photons we have assumed the effects of amplified spontaneous emission and residual facet reflectivities are insignificant [7]. The rate equations are different from those presented in [4] because we base the rate equations on the SOA model of [7].

Rate equations for LD A:

$$\frac{dP_A}{dt} = (\nu_g G_A - \frac{1}{\tau_p})P_A + \beta\frac{N_A}{\tau_e} \tag{1}$$

$$\frac{dN_A}{dt} = \frac{I_A}{q} - \frac{N_A}{\tau_e} - \nu_g G_A(P_A + S_{2avA}(\eta P_B + P_{Aext})) \tag{2}$$

Rate equations for LD B:

$$\frac{dP_B}{dt} = (\nu_g G_B - \frac{1}{\tau_p})P_B + \beta\frac{N_B}{\tau_e} \tag{3}$$

$$\frac{dN_B}{dt} = \frac{I_B}{q} - \frac{N_B}{\tau_e} - \nu_g G_B(P_B + S_{2avB}(\eta P_A + P_{Bext})) \tag{4}$$

Where

$$S_{2av} = \frac{e^{(G_A-\alpha_{int})L} - 1}{2L(G_A - \alpha_{int})} \tag{5}$$

$$G_A = \frac{\Gamma a}{V}(N_A - N_0) \tag{6}$$

S_{2avB} (from [7]) and G_B are similarly defined for LD B, but are dependent on N_B, rather than N_A.

The photon lifetime τ_p is given by

$$\frac{1}{\tau_p} = \nu_g(\alpha_{int} + \frac{1}{2L}\ln(\frac{1}{R_1R_2})) \tag{7}$$

R_1 , R_2 are the reflectivities of the wavelength dependent mirrors associated with each LD.

In (2) and (4), P_{Aext} and P_{Bext} represent the number of externally injected photons per LD cavity round trip time ($2L/\nu_g$ seconds), and are used to change the flip flop state. η is a coupling factor indicating the fraction of the photons

from one LD that are coupled into the other LD. Furthermore, from the right most terms of equations (2) and (4) it can be seen that only λ_1 wavelength photons (P_A) from LD A are injected into LD B, and only λ_2 wavelength photons (P_B) from LD B are injected into LD A.

τ_e is the carrier lifetime, and the other symbols have their usual meaning.

We consider the steady state behaviour of the flip flop. N_A, N_B, P_A and P_B can be considered state variables of the flip flop, as the set of four variables describe a unique operating point of the flip flop. The state variable steady state values were found by solving the rate equations numerically using a fourth order Runge-Kutta method. The state variables were determined for various values of injected external light P_{Bext} starting at $P_{Bext} = 0$. P_{Aext} was set to zero. For each value of P_{Bext} the state variables were found with the flip flop initially in state 1 and also initially in state 2. The simulation parameters were: $R_1 = R_2 = 0.02$, $\eta = 0.32$, $I_A = I_B = 158$ mA, $\tau_e = 1$ ns, $q = 1.6 \times 10^{-19}$ C, $\beta = 5 \times 10^{-5}$, $\nu_g = 8 \times 10^9 cm\ s^{-1}$, $\Gamma = 0.33$, $a = 2.9 \times 10^{-16}\ cm^{-2}$, $V = 2.5 \times 10^{-10}\ cm^3$, $N_0 = 2.2 \times 10^8$, $\alpha_{int} = 27\, cm^{-1}$, $L = 500$ microns. The SOA parameters were for a 1550 nm SOA [8].

The flip flop action can be clearly seen when the state variables P_A and P_B are plotted against P_{Bext} , Figure 2. The wavelength of the P_{Bext} photons is not λ_2. If the flip flop is initially in state 2, then it remains in state 2 with LD B lasing until P_{Bext} reaches the level P_{thr}. At this point the flip flop abruptly changes to state 1 with LD A lasing. The flip flop remains in state 1 even if P_{Bext} returns to zero. If the flip flop is initially in state 1 then it remains in state 1 for all values of P_{Bext} . The behaviour of the flip flop is similar to that shown in Figure 2 when P_{Bext} is set to zero and P_{Aext} is varied.

It can be seen from the simulation results that the flip flop has some useful properties including: high contrast ratio and little change in output at the lasing wavelength before the threshold is reached for the LD which isn't being injected with external light.

III. Experiments

To demonstrate the operation of the flip flop a prototype was constructed in free space optics. LDs (Uniphase CQL806) were used which had an antireflection coating with residual reflectivity of 5×10^{-4} deposited on the front facet. The antireflection coated LDs function as SOAs. To form LDs as described in Section 1 and Section 2, diffraction gratings were used as wavelength dependent mirrors for the antireflection coated LDs.

The experimental setup is shown in Figure 3. Gratings G1 and G2 form frequency selective external cavities (that is, wavelength dependent mirrors) for the two LDs, forcing LD A to lase at $\lambda_1 = 684$ nm and LD B to lase at $\lambda_2 = 678.3$ nm. The zeroth order diffracted beams from G1 and G2 serve as output beams for LD A and B. The output beams pass through optical isolators and then gratings G3 and G4. This arrangement ensures that only λ_1 light is injected into LD B from LD A, and only λ_2 light is injected into LD A from LD B. The gratings G3 and G4 direct the appropriate wavelength of light to the photo-diodes. PD 1 detects optical power at wavelength λ_1 and PD 2 at wavelength λ_2. Beam splitters are used to allow injection of light from one LD to the other LD and also from an external source. $\lambda/2$ plates are used to adjust the light polarization throughout the setup.

To demonstrate the flip flop operation, the flip flop state was regularly toggled by injecting light pulses into the LD which was master in the current state. Two hundred microsecond wide pulses of light at wavelength 676.3 nm were injected into the master LD for the current state approximately every 10 milliseconds. The optical powers at wavelengths λ_1 and λ_2 were observed on an oscilloscope (via photo-diodes PD 1 and PD 2). The oscilloscope traces are shown in Figure 4. The switching between states every 10 milliseconds can be clearly seen. Furthermore the flip flop state is stable in the time between the state changes.

IV. Conclusion

An optical flip flop was proposed based on two simple lasers diodes which act as a master-slave pair. The two lasers are coupled so that only light at the lasing wavelength of one laser is injected into the other laser. The flip flop state at

any given time is determined by which laser is master and which is slave. Rate equations were used to model the flip flop. The steady state characteristics of the flip flop were obtained from the numerical solution of the rate equations.

Flip flop operation is not dependent on second order laser effects such as resonant frequency shifts or gain saturation. Hence the flip flop should be able to be implemented in a wide variety of technologies. Furthermore the novel flip flop structure is straightforward to implement.

The flip flop was experimentally demonstrated using laser diodes with antireflection coatings.

Acknowledgments

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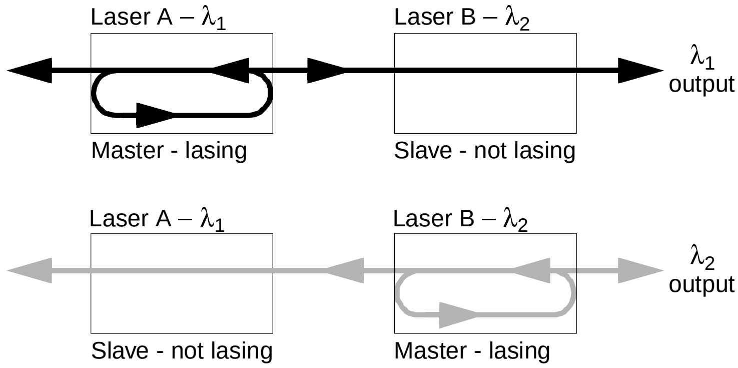
Figure Captions

Figure 1: Master-slave arrangement of two identical lasing cavities, showing the two possible states.

Figure 2: LD A and B photon numbers P_A , P_B versus external light injected into LD B P_{Bext}

Figure 3: Setup for optical flip flop. LD: laser diode antireflection coated facet, BS: beam splitter, G: diffraction grating, ISO: isolator, PD: photo-diode.

Figure 4: Optical power at the two lasing wavelengths, as measured by photo-diodes 1 and 2 in the experimental setup. The changing between the two states every 10 milli-seconds can be clearly seen.



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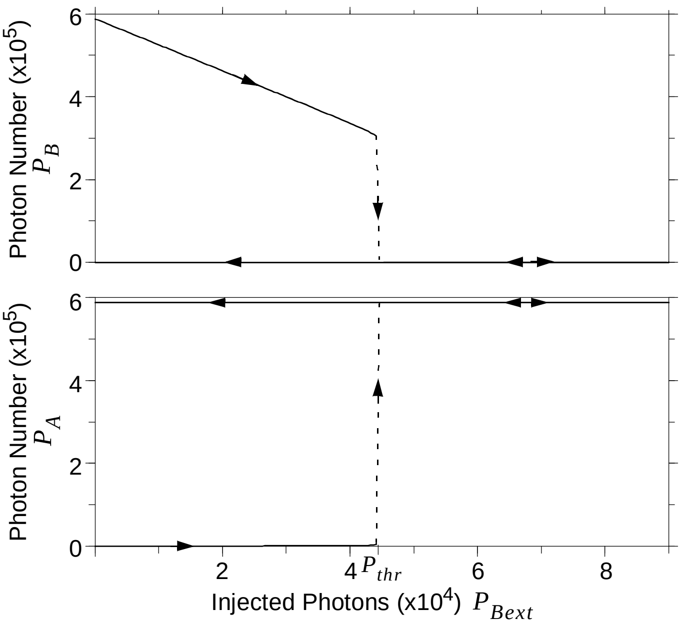

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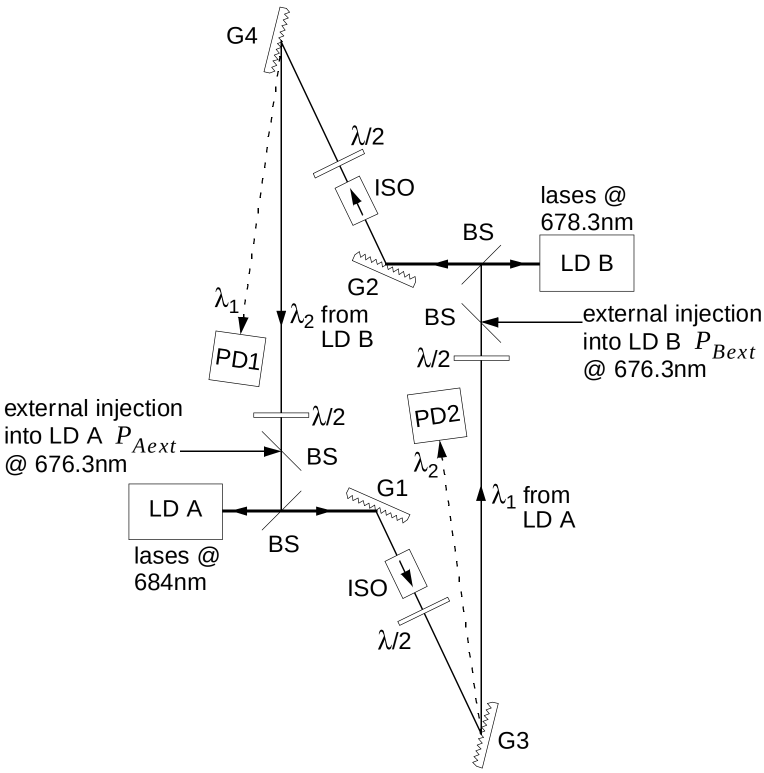

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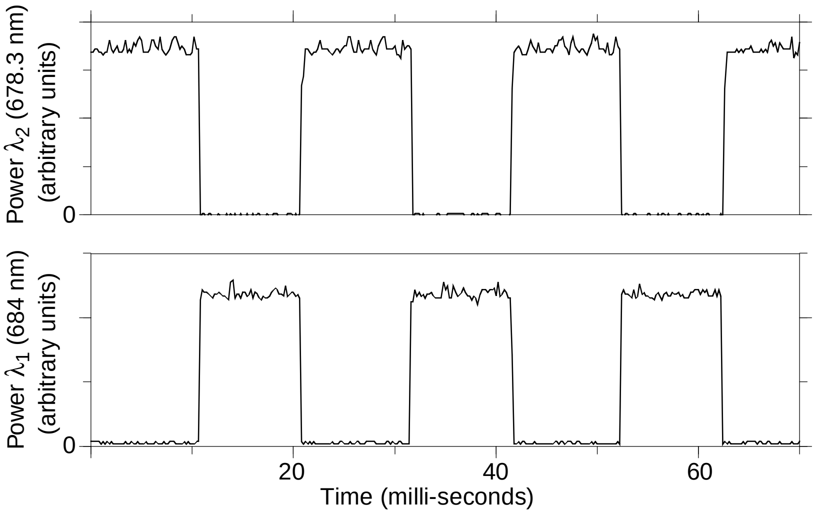

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